VEHICLE HOOD AND BUMPER STRUCTURE DESIGN TO MITIGATE CASUALTIES OF PEDESTRIAN ACCIDENTS

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ABSTRACT

Although the number of pedestrian fatalities and injuries is steadily declining worldwide, pedestrian protection is still an important issue. Extensive researches have been carried out for pedestrian protection in order to establish regulations for pedestrian safety. The automobile hoods and bumpers, which pedestrians frequently collide into during accidents, should be designed for the safety of the pedestrians.

Two analysis methods, a real experiment and computer simulation, are utilized to design safe structures of the hood and the bumper. A real experiment is very expensive while computer simulation has modeling imperfections. It would be optimal to obtain all the data from experiments to identify the design tendency. However, computer simulation is generally used due to budget restrictions.

In this research, a method, which uses an experiment and simulation simultaneously, is developed. Orthogonal arrays are employed to link the two methods. The minimum number of experiments is allocated to some rows of an orthogonal array and the simulations are allocated to the rest of the rows. Experiments should be allocated to have the cases of the experiments orthogonal. Mathematical error analysis is conducted. Based on the proposed methods, a hood and a bumper are designed to protect pedestrians. Real experiments and computer simulations are conducted for the rows of orthogonal arrays. The results show that the errors are distributed uniformly and a precise design is obtained.

INTRODUCTION

With the great number of pedestrian deaths and injuries occurring from automobile accidents, an effort is being made worldwide to establish automobile safety regulations for pedestrian protection. The hood and bumper, with which pedestrians come in frequent contact, can be designed and manufactured to be pedestrian friendly, effectively decreasing injuries [1-2]. During the development of a safe hood and bumper structures, experiments and computer simulations are used to evaluate their performances. Computer simulations contain many errors from inaccurate modeling and approximation of governing Equations. On the other hand, experiments are considered to be accurate even with the possibility of experimental errors and inaccuracies. In design, it would be the best if all the data could be obtained from experiments. However, an experiment is generally very costly. Therefore, limited experiments are performed in many application fields.

Orthogonal arrays are exploited very well for experiments with a limited number. They are used for the matrix experiments in design of experiments (DOE) [3]. When an experiment is extremely expensive, even the experiments with an orthogonal array are almost impossible to conduct in order to find a good design. In this case, some experiments can be replaced by computer simulations. As mentioned earlier, computer simulation has a large amount of errors [4].

A method is utilized to simultaneously use experiments and computer simulations in an orthogonal array. Experiments and simulations are assigned to the rows of an orthogonal array. The method of the assignment is proposed to minimize the error. The error is reduced since it is distributed evenly. The automobile hood and bumper structures are designed from the results of the orthogonal array. The results indicate that the proposed method finds design variables accurately [5].

EVALUATION OF PEDESTRIAN INJURIES

Pedestrian Accidents

Pedestrian accidents make up a large portion of traffic accidents. In the year 2000, pedestrian casualties numbered 19.0% (7,000) in Europe, 11.3% (4,739) in the U.S., 28.3% (2,605) in Japan, 38.0% (3,890) in Korea, and 50% (19,000) in China. There were also numerous cases of injuries - over 300,000 in Europe, 78,000 in the U.S., 86,000 in Japan and 74,102 in Korea [1-2][6].

Most pedestrian injuries (AIS 2-6) are head, face, and neck injuries, accounting for 36.9% and leg injuries accounting for 32.4% [7]. AIS (abbreviated injury scale) is an index used to classify injuries into 7 levels, from AIS 0 (no injuries) to AIS 6 (death). The greatest causes for head injuries are automobile windshields (33.5%), hood and wing surfaces (19.5%), and window frame and A-pillar (17.2%). The causes for leg injuries are bumpers (61.2%) and vertical parts of the hood (12.1%) [7].

Pedestrian Protection Regulations and Experiments

Impact test for pedestrian protection is implemented as illustrated in Figure 1 [6]. The experiment uses the standards of the impact experiments for the second stage child head model and the first stage lower body model in the Directive 70/156/EEC (2003/102/EC) [8]. The child head model is impacted on the hood. The horizontal impact angle is 50° with the wrap around distance (WAD) between 1,000-1,500mm. Impact speed is 40km/h and the required HIC (Head Injury Criterion) is 1,000 or lower. HIC is calculated from Equation (1) [6][8].

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \mathbf{a}\, dt \right]^{2.5} (t_2 - t_1) \qquad (1).$$

where $\mathbf{a}$ is the resultant acceleration measured in units of gravity "g"(1g = 9.81m/sec^2), t_1 and t_2 are the two time instances(expressed in seconds) during the impact, defining an interval between the beginning and the end of the recording period for which the value of HIC is the maximum ($t_2 - t_1 \leq$15msec).

A legform is used for the bumper impact test. Impact is applied to the bumper on at least three points where injuries or shape changes may result. Impact is imposed at 40km/h horizontally in line with the automobile. The maximum dynamic knee bending angle shall not exceed 21°, the maximum dynamic knee shearing displacement shall not exceed 6mm, and the acceleration measured at the upper end of the tibia shall not exceed 200g [6][8].

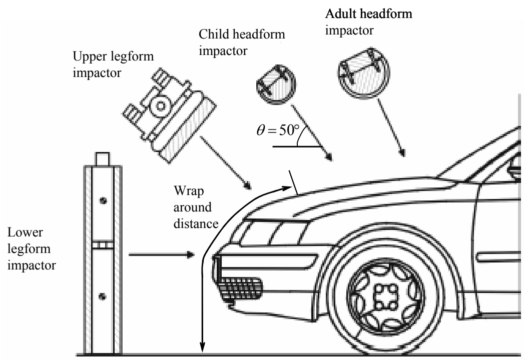

Figure 1. Schematic of impact experiments for pedestrian protection.

A DESIGN METHOD USING ORTHOGONAL ARRAYS WITH EXPERIMENTS AND COMPUTER SIMULATIONS

Using an optimization formulation, a design problem can be expressed as [4][9]:

$$\begin{aligned} &\text{Find } \mathbf{b} \in \mathrm{R}^n \\ &\text{to minimize } f(\mathbf{b}) \\ &\text{subject to } h_i(\mathbf{b}) = 0, \qquad i = 1, \cdots, k \\ &\qquad g_j(\mathbf{b}) \leq 0, \qquad j = 1, \cdots, l \\ &\qquad \mathbf{b}_\mathrm{L} \leq \mathbf{b} \leq \mathbf{b}_\mathrm{U} \end{aligned} \qquad (2).$$

where $\mathbf{b}$ is the design variable vector with n elements, f is the objective function, h_i is the i-th equality constraint, g_j is the j-th inequality constraint, and $\mathbf{b}_\mathrm{L}$ and $\mathbf{b}_\mathrm{U}$ are the vectors for lower and upper bounds of design variables, respectively. k is the number of equality constraint, and l is the number of inequality constraint. When an orthogonal array is used directly in design, the characteristic values are used by changing the functions in Equation (2).

Design Using Orthogonal Arrays

A full combination of experiments with design candidates can find the best design. However, real experiments are very expensive. Even computer simulation is costly for crashworthiness. In this case, orthogonal arrays are exploited well to replace the full combination to reduce the number of experiments [3-4][10]. Using the orthogonality of the rows in the orthogonal array, the minimum number of experiments is conducted. After the experiments of the rows are performed, a design is found by analysis of means (ANOM). The error variance is reduced due to the orthogonality [3-5].

Suppose we select the orthogonal array $L_9(3^4)$ where 9 is the number of rows, 3 is the number of levels, and 4 is the number of design variables. As shown in Table 1, an experiment is carried out for each row. The average of the characteristic values from $L_9(3^4)$ of Table 1 is

$$m = \frac{1}{9}\sum_{i=1}^{9}\eta_i \qquad (3).$$

where η_i is the characteristic value of the i-th row. When factor A is A_3, the average is m_{A_3} as

$$m_{A_3} = \frac{1}{3}(\eta_7 + \eta_8 + \eta_9) \qquad (4).$$

Table 1.
$L_9(3^4)$ **orthogonal array**

Exp. No.	Factor assigned				Characteristic value (η)
	A	B	C	D	
1	1	1	1	1	η_1
2	1	2	2	2	η_2
3	1	3	3	3	η_3
4	2	1	2	3	η_4
5	2	2	3	1	η_5
6	2	3	1	2	η_6
7	3	1	3	2	η_7
8	3	2	1	3	η_8
9	3	3	2	1	η_9

Therefore, the effect of level A_3 is $(m_{A_3} - m)$ when additivity is satisfied. Equation (4) is identical to Equation (5) by the additive model [11].

$$m_{A_3} = (\mu + a_3) + \frac{1}{3}(e_7 + e_8 + e_9) \qquad (5).$$

where μ is the true average value of η, a_3 is the true value of $(m_{A_3} - m)$ and e_j is the error of the j-th row of Table 1. When we use an orthogonal array to solve the problem in Equation (2), constraints exist. The characteristic function η is usually a function of the objective function f in Equation (2).

For constrained problems, the following augmented characteristic function η_{aug} is defined as:

$$\eta_{aug} = f + \bar{P} \qquad (6).$$

$$\bar{P} = \max(0, |h_i|; i = 1, \cdots, k,\ g_j; j = 1, \cdots, l) \times s \qquad (7).$$

where $\bar{P}$ is a penalty function defined from the maximum violation of the constraints and s is the scale factor. The size of the scale factor determines the way the constraints are considered. The constraints are usually normalized to fairly consider the constraints. η_{aug} is utilized instead of η in constrained problems.

A one-way table is established and the solution from the one-way table is intermediate design 1. The best one from the orthogonal array is intermediate design 2. In other words, η_i, which has the least objective function while constraints are satisfied, is intermediate design 2. Since interactions are not considered, a confirmation experiment should be conducted with intermediate design 1. If a constraint is violated by intermediate design 1, the design is discarded. Otherwise, intermediate design is compared with intermediate design 2 and the better one is selected for the final design [11].

A Method to Simultaneously Consider Experiments and Computer Simulations with an Orthogonal Array [4-5]

The method using experimental and computer simulation results simultaneously with an orthogonal array is explained. For example, if we have four design variables with three levels, orthogonal array $L_9(3^4)$ in Table 1 can be used. The standard deviation for error is σ_e and the standard deviation for the estimate m_{A_3} in Equation (5) is $1/3\sigma_e$. Assume that experiments are performed for rows 1, 5, 9 of the orthogonal array in Table 1 and computer simulations are performed for the rest. Suppose the standard deviation for the experimental error is σ_{ex} and the standard deviation for the error of computer simulation is σ_{sim}. It is assumed that $\sigma_{ex} << \sigma_{sim}$. Then Equation (5) yields

$$m_{A_3} = (\mu + a_3) + \frac{1}{3}(e_{sim} + e_{sim} + e_{ex}) \quad (8).$$

where e_{sim} is the simulation error and e_{ex} is the experimental error. The total error variance σ_E^2, when each error is independent, is as follows:

$$\sigma_E^2 = \frac{2}{9}\sigma_{sim}^2 + \frac{1}{9}\sigma_{ex}^2 \quad (9).$$

If $\sigma_e \cong \sigma_{sim} >> \sigma_{ex}$, then the error variance in Equation (9) is much less than the error variance in Equation (5). In rows 1, 5, 9 of Table 1, the design variables *A, B, C* are distributed so that each level equally appears. This will allow identical decrease in error variance for each level.

DESIGNING AN AUTOMOBILE HOOD AND BUMPER STRUCTURE

An automobile hood and bumper structure is designed to reduce pedestrian injuries. A "variable frontal structure" is installed to the test vehicle. This structure includes the hood and the bumper of a compact car. It allows adjustment of structural members which are design variables. The adjustment is made for each row of the selected orthogonal array. $L_9(3^4)$ orthogonal array is selected for the hood structure and $L_{18}(2^1 \times 3^7)$ orthogonal array is selected for the bumper structure. At the same time, the finite element model is established for each row of the orthogonal arrays.

The flow of the design process is illustrated in Figure 2. A design where only computer simulation results are used for each case in the existing orthogonal array and a design where both experimental and simulation results are used, are compared. A commercial finite analysis program LS-DYNA ([12]) was used for analyzing the hood and bumper structures.

Design of the Hood Structure

For the hood structure, three design variables *A*, *B* and *C* are selected. They are *A* = height of the striker which is the locking device on the front part of the hood; *B* = number of holes in the inner frame supporting the hood panel; *C* = height of the hinge which is a fastening device on the rear part of the hood [5][13]. For the parameter study of the design variables, impact is applied on three points of the hood at the places between 1,000-1,500mm of the wrap around distance (WAD). The child headform is impacted on the three points.

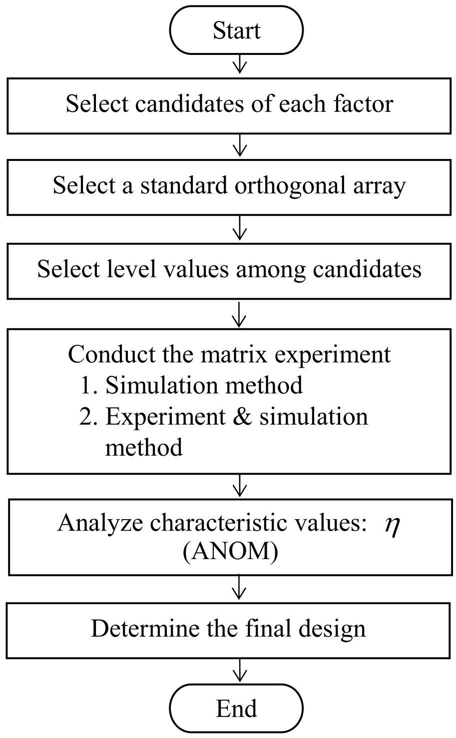

Figure 2. Flow of the design process.

Figure 3 presents the design variables and the impact points. P_1 in Figure 3 affects the striker and the hinge (design variable *A*), P_2 affects the hood frame holes (design variable *B*), and P_3 affects the inner structures of the engine room (design variable *C*) [5][12]. Design variables are determined by considering the tests on these three points. The neighbor of P_3 is stiffer than the other places, therefore, a larger weighting factor is imposed on the characteristic function for P_3.

The design problem is formulated as:

Find *A*, *B*, *C*

to minimize

$$\eta = 0.3HIC_{P_1} + 0.3HIC_{P_2} + 0.4HIC_{P_3}$$

subject to

$$HIC_{P_1} \le 1000$$
$$HIC_{P_2} \le 1000 \quad (10).$$
$$HIC_{P_3} \le 1000$$

where HIC_{P_i} is the HIC value at point P_i of Figure 3. The level values for design variables are defined by A (mm) = {0, 10, 20}, B (ea) = {0, 7, 16} and C (mm) = {0, 20, 40}.

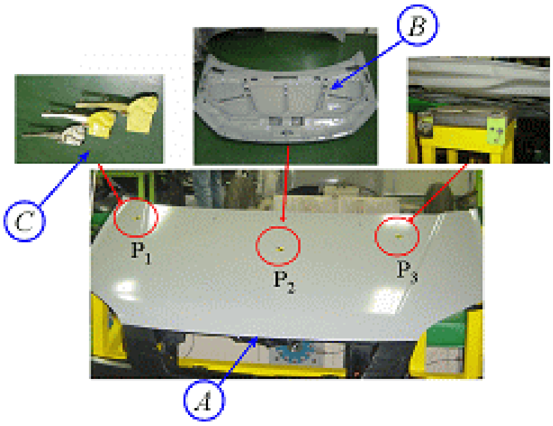

Figure 3. Impact points and design variables of the hood structure.

The Design Process of the Hood Structure Using Computer Simulation

Experiments and computer simulation are performed to evaluate the system. The finite element model is presented in Figure 4. The test facility with a "variable frontal structure," is shown in Figure 5. The first experiment is performed with respect to the first row of Table 2. For this case, the finite element model is tuned to match the simulation results with the experimental results. Then the finite element model is regarded as the established one. Computer simulations are performed for all the rows of Table 2. The results are shown in Table 2.

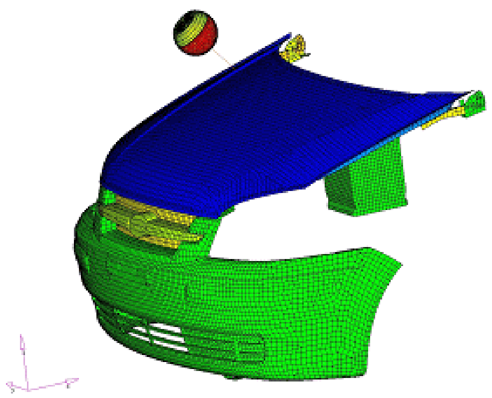

Figure 4. FE model of the child headform impact test.

Table 2.
$L_9(3^4)$ orthogonal array using computer simulation for the hood structure

Exp. No.	Factor assigned			Characteristic value		
	A	B	C	η	$\bar{P}$	η_{aug}
1	1	1	1	989.9	204.0	1193.8 √
2	1	2	2	839.3	25.0	864.3 √
3	1	3	3	784.0	0.0	784.0
4	2	1	2	955.2	133.0	1088.2 √
5	2	2	3	832.5	0.0	832.3
6	2	3	1	785.5	0.0	785.5
7	3	1	3	963.8	153.0	1116.8 √
8	3	2	1	831.8	0.0	831.8
9	3	3	2	814.9	0.0	814.9

η_{aug} is defined from Equations (6) and (10) and the scale factor is set by s = 1. Rows 1, 2, 4 and 7 of Table 2 do not satisfy the constraints and are marked by √ on η_{aug}. Through the ANOM (one-way table), intermediate design 1 is found and it is A_2, B_3 and C_3. A simulation for confirmation is carried out with intermediate design 1. The result is that η_{aug} = 768.0 and the constraints are satisfied. Intermediate design 2 is selected from Table 2. It is the third row. The two designs are compared and the final solution is intermediate design 1. The final design is: striker height A = 10mm, numbers of hole in hood frame B = 6ea, and hinge height C = 40mm. The simulation for confirmation shows that HIC_{P_1} = 824.3, HIC_{P_2} = 605.7 and HIC_{P_3} = 847.6.

Design by Experiments and Computer Simulation for the Hood Structure

Experiments are performed in the facility in Figure 5. Experiments are prepared for rows 1, 5 and 6 of Table 3 and simulations are prepared for the remaining rows. η_{aug} and the scale factor are defined in the same manner as the previous process. The results with the $L_9(3^4)$ orthogonal array are shown in Table 3. Rows 1, 2, 4, 5 and 7 in Table 3 do not satisfy the constraints and are thus marked by √ in η_{aug}. A_2, B_3, C_3 are obtained as intermediate design 1 from the ANOM (one-way table).

Intermediate design 1 is confirmed by computer simulation. η_{aug} = 768.0 and the constraints are satisfied. Intermediate design 2 is the third row of Table 3. These results are the same as the previous results. Therefore, A_2, B_3 and C_3 are the final solution.

Figure 5. Child headform impact test setup.

Table 3.
$L_9(3^4)$ orthogonal array using experiments and computer simulation for the hood structure

Exp. No.	Factor assigned			Characteristic value		
	A	B	C	η	$\bar{P}$	η_{aug}
1	1	1	1	1056.1	225.5	1281.6 √
2	1	2	2	839.3	25.0	864.3 √
3	1	3	3	784.0	0.0	784.0
4	2	1	2	955.2	133.0	1088.2 √
5	2	2	3	795.0	35.0	830.3 √
6	2	3	1	785.5	0.0	785.5
7	3	1	3	963.8	153.0	1116.8 √
8	3	2	1	831.8	0.0	831.8
9	3	3	2	794.6	0.0	794.6

Design of the Bumper Structure

For the bumper test, a legform is impacted on the bumper. A bumper structure is presented in Figure 6. Five design variables are chosen as shown in Figure 6. They are A = distance between the edge of the hood and the edge of the bumper; B = thickness of the bumper foam absorbing the impact energy; C = distance between the edge of the stiffener (a structure to decrease the bend angle of the lower-body) and the edge of the bumper; D = strength of the bumper cross member; and E = bumper height [5][13]. Variable E is different for each vehicle model.

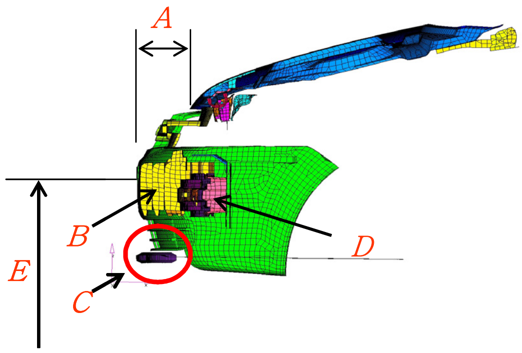

Figure 6. Design variables of the bumper structure.

Since there are five design variables and three levels, $L_{18}(2^1 \times 3^7)$ standard orthogonal array is selected [3]. The values of the design variables from an existing one are set to level 1's. Ones higher than the initial values are set to levels 2 and 3.

The problem is to find the levels of the five design variables to minimize the acceleration, the bending angle, and the shear displacement of the legform. The legform is impacted at a velocity of 40km/h to the center of the bumper structure. Since the acceleration and bending angle requirements are more difficult to satisfy, the corresponding weighting factors are larger. The problem is formulated as

Find A, B, C, D, E
to minimize

$$\eta = (0.45 \times \frac{accel}{200} + 0.45 \times \frac{bend\_angle}{21} + 0.10 \times \frac{shear\_disp}{6})$$

subject to

$$\begin{aligned} &accel. \le 200\,g \\ &bend.\_angle \le 21° \\ &shear\_disp. \le 6mm \end{aligned} \qquad (11).$$

where $accel.$ is the acceleration measured at the upper end of the tibia, $bend.\_angle$ is the maximum dynamic knee bending angle, $shear\_disp.$ is the maximum dynamic knee shearing displacement, and η is the characteristic function. Level values for the variables are A(mm) = {78, 105, 132}, B(mm) = {25, 50, 75}, C(mm) = {none, -25, 0}, D(ratio) = {1, 0.7, 0.5} and E(mm) = {0, 30, 60}.

The Design Process of the Bumper Structure Using Computer Simulation

Experiments and computer simulation are performed to evaluate the system. The finite element model is presented in Figure 7. The test facility with a "variable frontal structure," is shown in Figure 8. The first experiment is performed with respect to the first row of Table 4. The tuning process of the finite element model is the same as before. Computer simulations are performed for all the rows of Table 4. The results are shown in Table 4.

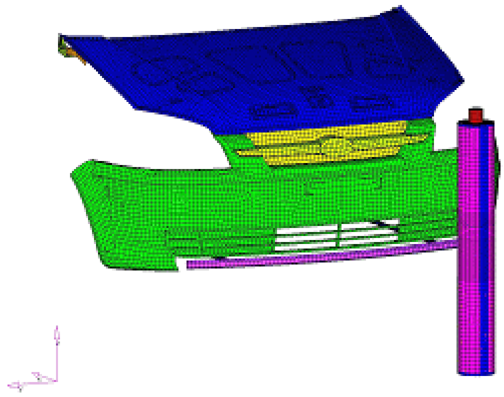

Figure 7. FE model of the lower legform impact test.

Table 4.
$L_{18}(2^1 \times 3^7)$ orthogonal array using computer simulation for the bumper structure

Exp. No.	Factor assigned					Characteristic value		
	A	B	C	D	E	η	$\bar{P}$	η_{aug}
1	1	1	1	1	1	1.325	0.688	2.010 √
2	2	2	2	2	2	1.063	0.310	1.373 √
3	3	3	3	3	3	1.026	0.097	1.122 √
4	1	1	2	2	3	1.329	0.557	1.886 √
5	2	2	3	3	1	0.782	0.000	0.782
6	3	3	1	1	2	1.152	0.695	1.847 √
7	1	2	1	3	2	1.109	0.667	1.775 √
8	2	3	2	1	3	1.339	0.538	1.877 √
9	3	1	3	2	1	0.997	0.106	1.103 √
10	1	3	3	2	2	0.690	0.000	0.690
11	2	1	1	3	3	1.238	0.829	2.067 √
12	3	2	2	1	1	0.820	0.000	0.820
13	1	2	3	1	3	1.030	0.104	1.134 √
14	2	3	1	2	1	1.098	0.629	1.726 √
15	3	1	2	3	2	1.108	0.238	1.346 √
16	1	3	2	3	1	0.942	0.065	1.007 √
17	2	1	3	1	2	0.983	0.072	1.054 √
18	3	2	1	2	3	1.192	0.776	1.968 √

η_{aug} is defined from Equations (6) and (11) and the scale factor is set by s = 1. All the rows except for rows 5, 10, and 12 do not satisfy the constraints and are marked by √ on η_{aug}. Intermediate design 1 is A_3, B_2, C_3, D_3 and E_1. From the simulation for confirmation, η_{aug} = 0.587 and the constraints are satisfied. The acceleration is 166.5g, the knee bending angle is 8.3°, and the shearing displacement is 2.1mm. Intermediate design 2 is the tenth row of Table 4. Since intermediate design 1 is better, it is selected as the final solution. The solution is A = 132mm, B = 50mm, C = 0mm, D = 0.5 and E = 0mm.

Design by Experiments and Computer Simulation for the Bumper Structure

Experiments are carried out by the facility in Figure 8. Experiments are performed for rows 1-6 of Table 5 where each level of a design variable appears twice. Computer simulations are carried out for the rest of the rows. As shown in Table 5, all the rows except for rows 3, 5, 10, 12 do not to satisfy the constraints and are marked by √ on η_{aug}. Intermediate design 1 is A_3, B_2, C_3, D_3 and E_1.

Figure 8. Lower legform impact test setup.

Computer simulation is conducted for confirmation with intermediate design 1. The results are η_{aug} = 0.587, acceleration = 166.5g, knee bending angle = 8.3°, and shearing displacement = 2.1mm. The constraints are satisfied. Intermediate design 2 is obtained from Table 5. It is the third row with A_3, B_3, C_3, D_3 and E_3. Since intermediate design 2 is better, it is chosen as the final solution. The final solution is A = 132mm, B = 75mm, C = 0mm, D = 0.5, and E = 60mm. For the final solution, the acceleration is 86.6g, the knee bend angle is 15.2° and the shear displacement is 2.7mm.

Table 5.
$L_{18}(2^1 \times 3^7)$ orthogonal array using experiments and computer simulation for the bumper structure

Exp. No.	Factor assigned					Characteristic value		
	A	B	C	D	E	η	$\bar{P}$	η_{aug}
1	1	1	1	1	1	1.348	0.614	1.962 √
2	2	2	2	2	2	0.816	0.143	0.957 √
3	3	3	3	3	3	0.565	0.000	0.565
4	1	1	2	2	3	1.007	0.257	1.265 √
5	2	2	3	3	1	0.588	0.000	0.588
6	3	3	1	1	2	1.055	0.657	1.712 √
7	1	2	1	3	2	1.109	0.667	1.775 √
8	2	3	2	1	3	1.339	0.538	1.877 √
9	3	1	3	2	1	0.997	0.106	1.103 √
10	1	3	3	2	2	0.690	0.000	0.690
11	2	1	1	3	3	1.238	0.829	2.067 √
12	3	2	2	1	1	0.820	0.000	0.820
13	1	2	3	1	3	1.030	0.104	1.134 √
14	2	3	1	2	1	1.098	0.629	1.726 √
15	3	1	2	3	2	1.108	0.238	1.346 √
16	1	3	2	3	1	0.942	0.065	1.007 √
17	2	1	3	1	2	0.983	0.072	1.054 √
18	3	2	1	2	3	1.192	0.776	1.968 √

Discussion

The two methods give the same solution in the design of the hood structure. However, they give different solutions in the design of the bumper structure. The designs are improved in both cases. Computer simulations contain large amount of errors that can change the design results. Therefore, when experiments and simulations are simultaneously used, a more precise solution can be obtained.

CONCLUSIONS

From this research, the followings are concluded:

1) A new method is proposed to use experiments and computer simulation in design. Orthogonal arrays are employed in the design process. Error analysis is conducted for the method. Automobile hood and bumper structures are designed for pedestrian protection by using the proposed method.

2) Designs are carried out in two methods - one utilizing only computer simulation, and one utilizing experiments and computer simulation. The results from the two methods are compared. Precise solution is obtained from the method by using experiments and computer simulation because the errors are reduced.

3) The final design of this research is for pedestrian protection. More researches are needed to see if the design satisfies other regulations on frontal impacts, offset impacts and bumper impacts, etc.

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